Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24,** 111–125 (1999)

CLAST EXPOSURE ON BOULDER-COVERED DESERT SLOPES

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Received 16 March 1998; Revised 28 July 1998; Accepted 11 August 1998

ABSTRACT

Variation in the degree of clast exposure on stony desert slopes is examined in an area of northeast Jordan. Geological influences on the characteristics of stone mantles are modified by relative slope position. Observations that the nature of the surface stone cover changes downslope because of the transport and accumulation of the underlying substrate are confirmed by quantitative analysis. An elliptic function is described as a means of estimating relative clast exposure from simple field measurements of clast dimensions. There are no significant differences in mean clast exposure between the four main basalt lithologies of the study area, but a distinctive pattern of clast exposure catenas can be identified. Convex slopes maintain relatively high levels of clast exposure from crest to toe. About two-thirds of the variation in clast exposure is accounted for by lithology and four slope variables: relative relief, slope length, gradient and curvature. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: stone mantle; clast exposure; basalt; slope wash

INTRODUCTION

Stone surfaces are characteristic of many desert areas. The interaction of surface stone cover with underlying sediment has been shown to be an important control on the hydrological and erosional response of slopes (Abrahams and Parsons, 1991; Poeson and Lavee, 1994; Dunkerley, 1995). The protective armouring of the fine grained surface is, to some extent, counteracted if the clasts are embedded within the surface. Variations in clast cover and exposure characteristics in relation to lithology and slope position may therefore be significant in controlling infiltration and surface runoff. No previous study appears to have been attempted to quantify the relative exposure and burial of stones along slope profiles. Since the estimation of this property remains problematic, a study was completed to establish a rapid field method of estimating the proportion of clasts exposed above sediment surfaces using a quantifiable index based on an elliptic function. The index can be used to explain downslope variations in boulder exposure/burial property in terms of slope, profile form, geology and clast dimensions.

THE STUDY AREA

In parts of the Eastern Badia of Jordan, boulder-strewn surfaces formed above a series of late Tertiary and Quaternary basalts dominate the landscape. In most situations, the clasts form a surface armour over an orange–brown silty deposit. The size and spacing of basalt clasts varies between different lava types such that a change in surface boulder characteristics is often the first indication of a change in the underlying lithology. At least four processes have been proposed to explain the evolution and survival of surface pavements in other locations (Wainwright *et al.*, 1995): the upward migration of clasts through the regolith; selective deflation of fines; erosion of fines by slope wash; inter-clast infiltration of aeolian fines. Observation of boulder surfaces along slope profiles clearly indicates the importance of slope wash in transporting the underlying sediment downslope. The thickness of the deposit increases downslope such that towards the base of the slope many of the clasts are partially buried within the sediment.

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Contract/grant sponsor: Jordan Badia Research and Development Programme
Contract/grant sponsor: University of Durham Research Initiatives Fund

CCC 0197-9337/99/020111–15 $17.50

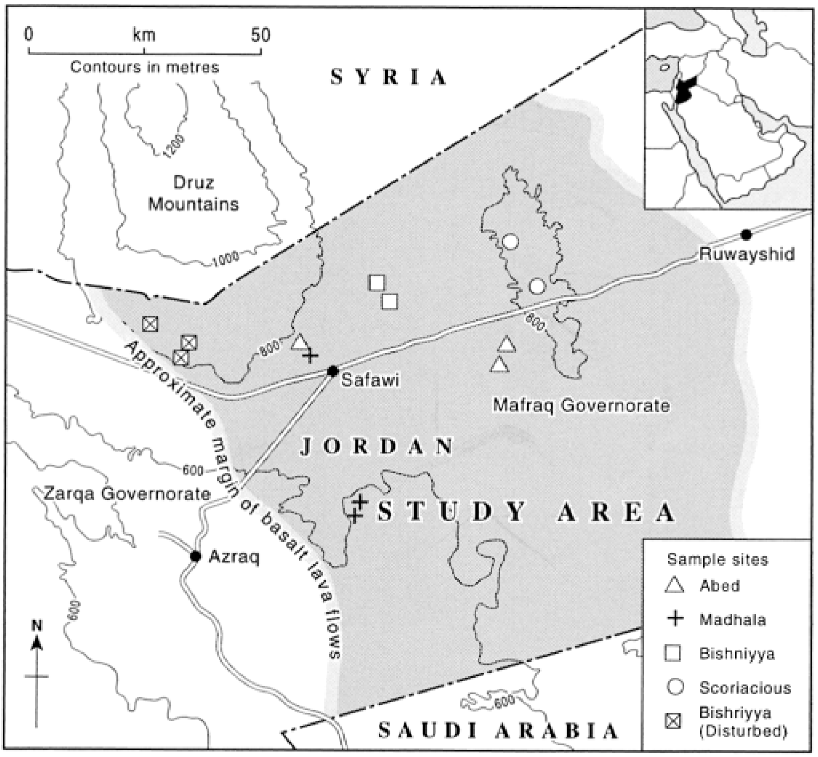

Figure 1. Location of sample sites within the Eastern Badia study area

The study area (Figure 1) is an arid landscape in which precipitation is irregular and seldom exceeds 200 mm a^{-1}. The orographic effect of the Druz Mountains raises annual precipitation totals to around 350 mm in the northwest of the study area and there are a number of villages located here. There is some archaeological evidence that the extent of rain-fed agriculture may have been more extensive in the past, promoting disturbance of the boulder surfaces (Betts, 1992; Kirk, 1998).

Geologically the area is dominated by late Tertiary and Quaternary basalts which are alkali-olivine in character (Ibrahim, 1992). Early geological investigations divide the basalts into three groups: older, middle and younger flows (Bender, 1974) although subsequent work has recognized further subdivisions of the record. In the present study three basalts of different ages have been selected for study: the Abed, Madhala and Bishriyya. All are part of the Harrat Ash-Shaam supergroup and of different character and age. The Abed is the oldest exposed basalt at approximately 8·9 million years. It is an olivine picrite and is characterized geomorphologically by an open matrix of angular boulders up to 50 cm in diameter, exposing the underlying orange–brown sediment between clasts. The Madhala basalt is also an olivine picrite and is dated to between 1·96 and 3·41 million years. The Madhala also presents an open matrix but individual clasts are typically smaller, up to 25 cm diameter (Figure 2). The Bishriyya is the most recent lava flow in the area and is dated between 0·1 to 1·45 million years. Boulder surfaces are characterized by vesicular clasts with limited exposure of fine-grained sediment. In addition to the basalt lava flows, there are a number of scoriacious volcanic deposits around recent volcanic cones and associated with a contemporaneous dyke system (Figure 3).

The topography of the study area comprises a gently rolling basalt plateau, punctuated by peaks which mark the location of recent volcanic spreading centres. The altitude across the region gradually declines from 1200 m on the footslopes of the Druz Mountains in the north to around 400 m in the south. Apart from the individual volcanic cones gradients are slight but there is considerable variation

Figure 2. Open matrix boulder cover on Madhala lava

Figure 3. Boulder cover of scoriacious material on a steeply concave slope associated with recent (*c.* 0·1 Ma) eruptive activity

in slope length, curvature and relative relief. The basalt flows are dissected by a series of wadis which generally drain to the south or southeast from the Druz mountains. Drainage networks are punctuated by sedimentary pans and are poorly developed on the Bishriyya basalt, where local drainage is principally controlled by the location of pressure ridges in the original flow. An earlier paper (Allison and Higgitt, 1998) has described the range of slope types in the Eastern Badia and discussed the general association between boulder surface characteristics and slopes. The analysis concluded that

geological controls are the primary influence on the size of clasts present at the surface and of the percentage ground cover which they occupy but that pavement characteristics are modified by slope position. Here, the relationship between clast exposure and slope characteristics is examined in further detail.

METHODS

Field survey of clast cover characteristics

The sampling framework for investigating boulder cover characteristics was undertaken in conjunction with a slope profile survey. Sampling was conducted on 13 slope profiles representing the four different types of lithology (three basalt types plus scoriacious deposits) and a variety of profile shapes and lengths. Three of the slope profiles on Bishriyya basalt have been disturbed by human activity at some stage in the past, which has altered the ground surface characteristics. For the purposes of analysis, the disturbed Bishriyya slopes are considered separately, such that the sample sites are classified into five geological categories: Abed, Madhala, Bishriyya, Scoriacious and Disturbed.

Along each slope profile, five points were positioned at the same relative location: crest, upper, mid, lower and toe. At each point a 2 m by 2 m quadrat was established on the ground and a number of measurements undertaken. A quadrat sampling strategy was used in preference to a grid-based sampling framework, where clasts are measured at the intersection of grid nodes over a larger area. The latter method is time consuming and requires careful correction of measurements to avoid bias associated with the likelihood of larger particles occurring at grid nodes (Dunkerley, 1996). The quadrat measurement routine has logistic advantages, enabling measurements to be undertaken speedily by two field operators. Measurement of all the exposed dimensions of clasts, where A-axis $\geqslant 100$ mm, enables a variety of size, sorting and ground cover indices to be calculated. One of the slope profiles on the Madhala Basalt drops abruptly into an incised wadi, such that no toe slope location can be identified. Consequently, the boulder data set contains 64 quadrat sites on 13 profiles, grouped into five geological and five slope position categories.

The slope profiles were surveyed with a Leica TC1010 total station, with spot heights calculated at distances of about 5 m. The co-ordinates of the corners of each quadrat were located during the slope survey. Following analysis of the slope profiles, a number of slope variables were calculated for each quadrat site. Thus the relative slope position category can be augmented by quantitative variables including: height above toe elevation, H (m); relative relief, R (per cent); and distance downslope from crest, L (m). Gradient attributes were calculated by examining changes in elevation over a distance of six survey lengths above and below the quadrat location, with minor modification for crest and toe sites. Hence, slope gradient, θ (degrees), represents the average angle over a distance of approximately 30 m. Slope curvature, C_v (degrees per 100 m), is calculated as the change in slope gradient over the same distance. The mean gradient below the quadrat site is subtracted from the mean gradient above. Positive values indicate concave elements and negative values convex elements. In addition, quadrat gradient, θ_q (degrees), was calculated from the mean elevation difference between the upper and lower corners of the quadrat. In general terms, slope gradient and plot gradient are very similar but there are occasional differences due to the step-like microtopography on some slopes. A number of erosion indices can be calculated from gradient and slope length variables.

Estimation of clast exposure

The extent to which boulders are exposed above or buried within the underlying fine sediment can be identified clearly in the field because of the visible staining where the rock surface has been in contact with the sediment. At each of the sampling locations, 10 clasts, selected at random within a 5 m radius of the quadrat, were carefully exhumed and the proportions of stained and unstained surfaces measured. The computation of part volumes of ellipsoids is not straightforward and the field measurement of clasts

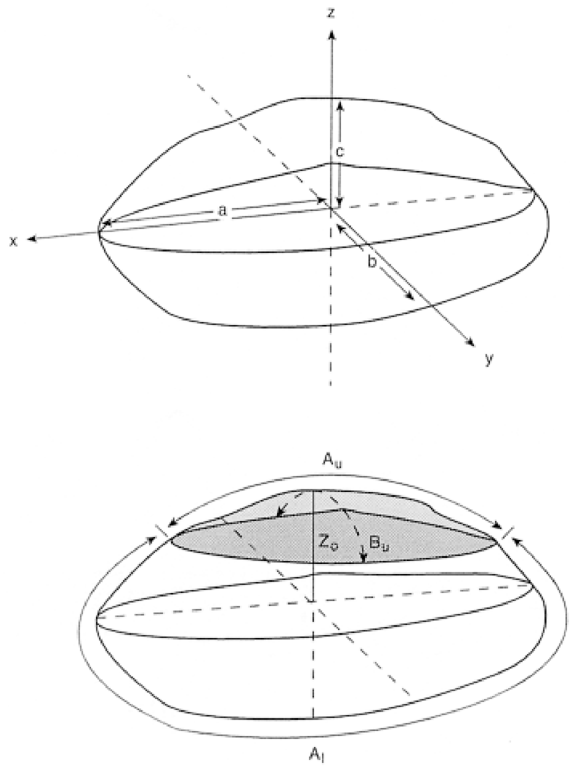

Figure 4. Measurements for estimating clast exposure

had to provide relevant dimensions for calculating exposed volumes efficiently. Nine dimensions were measured on each clast: the conventional long, intermediate and short axes; the circumferences around the exposed and buried portions of the long and intermediate axes; and the length of the short axis above and below the staining line (Figure 4). In order to avoid confusion between the algebraic and sedimentological use of the axis labels (a, b, c), where the former indicate radii and the latter diameters, the following convention is employed, with all units measured in centimetres:

a = long axis radius of ellipsoid (plotted along x-axis);
b = intermediate axis radius of ellipsoid (plotted along y-axis);
c = short axis radius of ellipsoid (plotted along z-axis);
A, B, C = measured long, intermediate and short axis diameters of clasts;
A_U, B_U = measured long and intermediate circumferences of lower (exposed) surface;
A_L, B_L = measured long and intermediate circumferences of lower (buried) surface;
A_T, B_T = measured circumference around long and intermediate axis ($A_T = A_U + A_L$);
C_U, C_L = measured length of short axis above and below staining line, respectively.

The measured circumferences around the long and intermediate axes can be compared to the theoretical approximation of the perimeter of an ellipse. The perimeter of the a-axis rotated around the c-axis is given by:

$$3ac - \sqrt{(a+3c)(3a+c)} \tag{1}$$

The measured circumferences around both the long and intermediate axes compare favourably with the modelled values (Figure 5). The occasional large deviation between the measured and predicted circumference is attributed to the irregular shape of clasts, but the total deviation between measured and

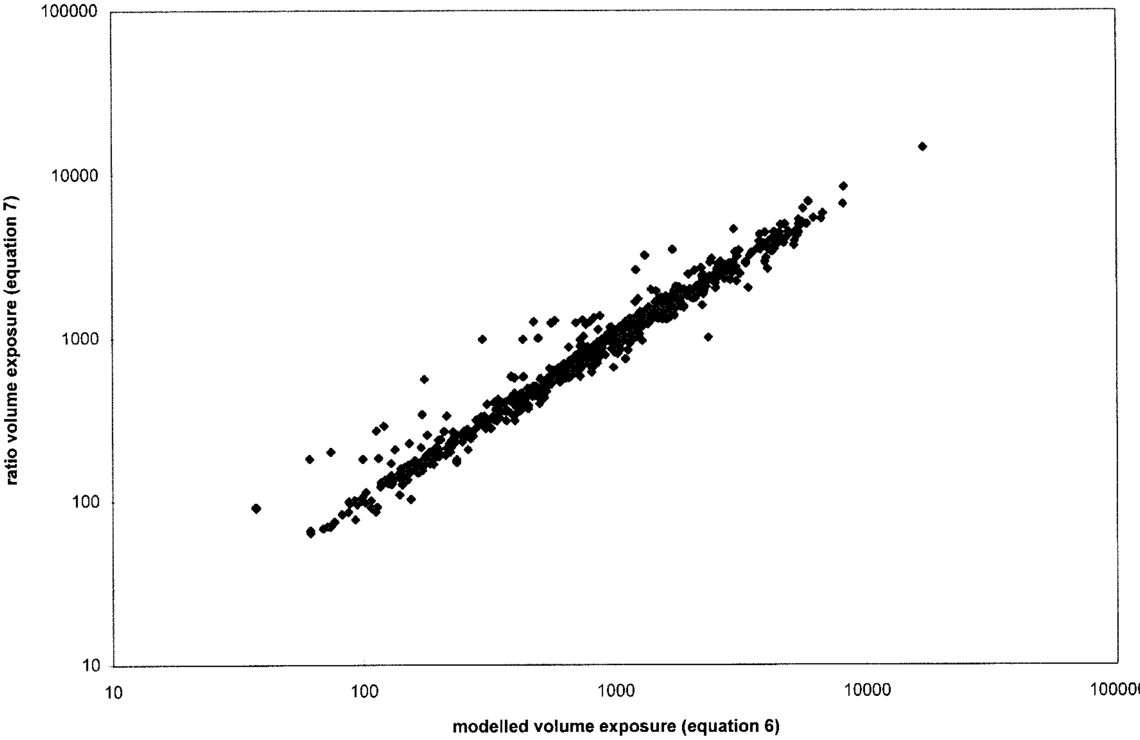

Figure 5. Comparison of clast exposure estimates from elliptic model (Equation 6) and ratio of exposed and buried circumferences (Equation 7)

predicted values is +2·8 per cent for long axis circumference and –0·6 per cent for the intermediate axis circumference. The volume of an ellipsoid can be approximated by:

$$V = 4/3\pi\ abc \tag{2}$$

The equation of the ellipsoid is given as:

$$x^2/a^2 + y^2/b^2 + z^2/c^2 = 1 \tag{3}$$

and the volume derived by the integral

$$V = 8\int_0^a \int_0^{b(1-x^2/a^2)^{1/2}} \int_0^{c(1-x^2/a^2-y^2/b^2)^{1/2}} \mathrm{d}x\ \mathrm{d}y\ \mathrm{d}z \tag{4}$$

When the soil surface height is indicated by z_0, the volume above the soil surface is given as:

$$\pi\ a\ b\left[z - z^3/3c^2\right]_{z_0}^{a} \tag{5}$$

$$= \pi\ a\ b\ (2/3a - z_0(1 - (z_0^2/3c^2))) \tag{6}$$

Equation 6 can be used to calculate the exposed volume by substituting $A/2$, $B/2$, $C/2$ for a, b, c, and $(C/2–C_U)$ for z_0. Alternatively, the relative burial and exposure of clasts can be estimated from the ratio of the stained and unstained circumferences. As the ratio varies for each axis, an average ratio is provided by:

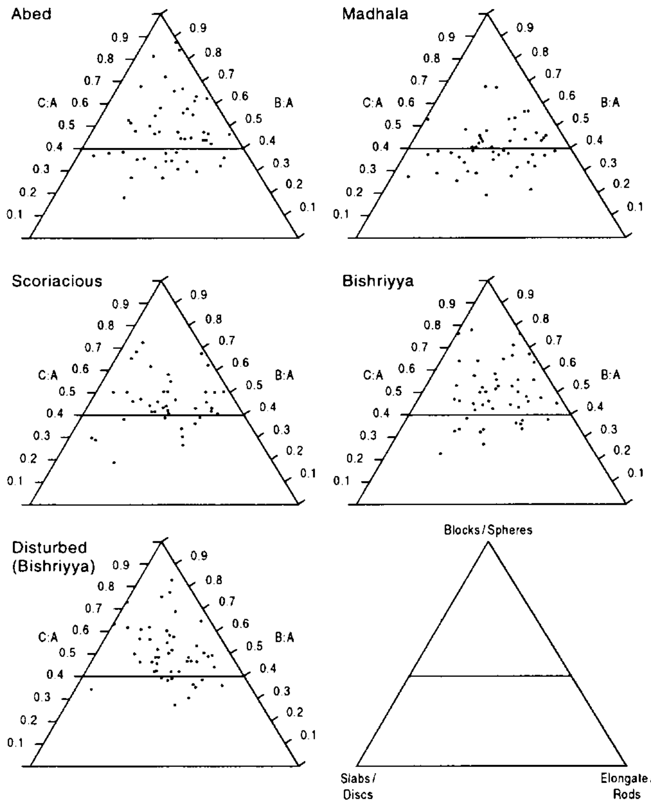

Figure 6. Clast shape ternary diagrams for one slope profile from each geological category

$$(A_{\mathrm{U}}/A_{\mathrm{T}} + B_{\mathrm{U}}/B_{\mathrm{T}} + C_{\mathrm{U}}/C)/3 \tag{7}$$

A comparison of exposed clast volumes calculated by Equations 6 and 7, indicates good agreement (Figure 5). Total deviation between the modelled and ratio estimates is –3·1 per cent. Estimates of partial clast volumes are compromised by clast irregularity and by the surface contact effect. A perfect ellipsoid completely exposed above a smooth substrate will be in contact with the surface at one point. In reality, an exposed clast resting on the substrate will have a substantial area of staining because of the roughness of the surface and the compression imposed by the weight of the clast. The estimation of clast exposure provided by Equation 6 is sensitive to the value of C_{L}, and hence z_0. Nevertheless, the agreement between the two methods suggests that the equation is a viable means of estimating the relative exposure of clasts.

The suitability of the ellipsoid approximation can be examined by representing the shape and regularity characteristics of the sampled boulders. Following the procedure recommended by Benn and Ballantyne (1993), primary axis data for all sampled clasts on one slope profile from each geological category has been plotted on a ternary diagram (Figure 6). The diagrams plot the C:A ratio against the B:A ratio indicating the tendency for clasts to resemble spheres/blocks, discs/slabs and rods/elongate. The distribution of points indicates that clast shape characteristics within each group are generally scattered. There is limited distinction between geological types although there is some suggestion that the more recent materials (Scoriacious and Bishriyya) are generally less elongate or slabby than the older lavas (Abed and Madhala). The regularity of clast shape can be examined by comparing the measured circumference of sampled boulders with the theoretical ellipsoid perimeter (Equation 1). The measured

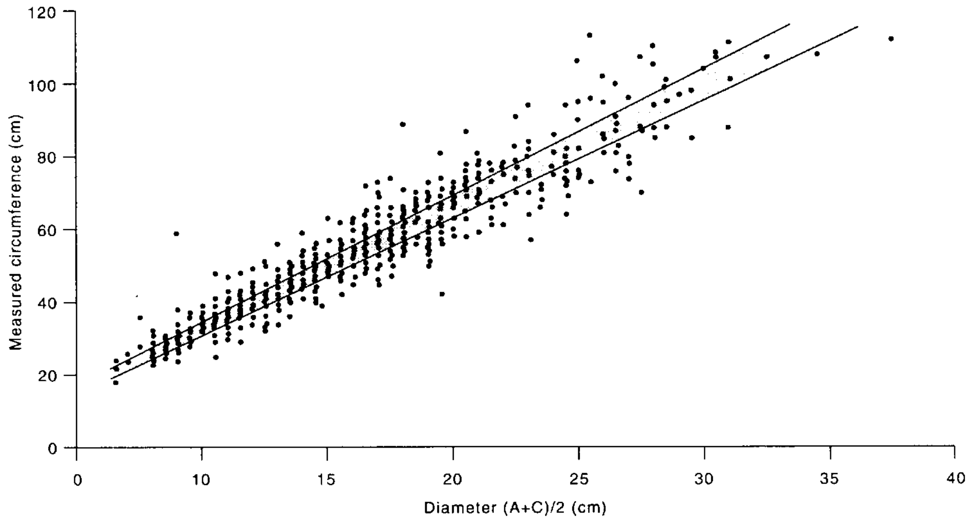

Figure 7. Comparison of measured and predicted long axis circumference. The shaded area indicates the range of circumferences for perfect ellipsoids.

circumference of the A-axis rotated around the *C*-axis is plotted against the mean *A* and *C* diameter length (Figure 7). The shaded area indicates the range of predicted ellipsoid circumferences for the given *A*- and *C*-axis diameter combinations. Although a number of points plot outside the modelled range, there is an approximate balance in the number of points above (increasingly blocky) and below (increasingly sub-ellipsoid) the range, such that the use of the ellipsoid model for an approximation of relative clast exposure appears justified. Distant outliers from the stippled range indicate individual clasts which have been buried across *A* or *B* axes rather than the *C* axis.

The percentage exposure at each sampling site is weighted by volume, exposed volume of 10 clasts/total volume of 10 clasts, in an attempt to reduce bias introduced by variations in clast size within samples. As the primary aim of the paper is to investigate lithological and slope position controls on relative clast exposure, an index based on net volume exposure is justified, although it might be argued that volume-weighting of mean exposure would give undue emphasis to the exposure fraction of large stones within the sample. Dunkerley (1995) has highlighted the difficulties associated with parameterizing stone cover on desert surfaces and has advocated the use of stone characteristics weighted by perimeter or surface area dimensions as being more meaningful hydrologically than either arithmetic or volume-weighted measurements. The value of perimeter and surface area-weighted measurements for describing other aspects of the boulder cover characteristics has been investigated in another paper (Higgitt and Allison, in press). The performance of exposure estimation and variations in clast exposure according to slope variables and lithological controls can be investigated based on the above measurements and their associated functions.

RESULTS

Geological controls appear to be the primary influence on the size of clasts and total ground cover. Consistent patterns of size, sorting and exposure characteristics along slope profiles emerge within individual basalt types. A detailed analysis of exposure characteristics requires examination of the variability between lithologies and distribution along slope profiles and analysis of exposure characteristics with slope variables.

The mean clast exposure and standard deviations for each lithology is presented in Table I. The mean

Table I. Mean clast exposure grouped by lithological category

Basalt	Estimated age (Ma)	Slope forms (see Figure 8)	Mean stone cover (number m^{-2})	Mean exposure (%)	Standard deviation
Abed	8·9	convex, convex–rectilinear	17·2	62·8	16·4
Madhala	2·0–3·4	concave to convex	20·9	61·2	10·4
Bishriyya	0·1–1·5	concave, concave–rectilinear	25·0	58·1	18·3
Scoriacious	0·1	concave	12·0	61·7	16·3
Disturbed sites (Bishriyya)	0·1–1·5	concave, concave–rectilinear	11·0	46·1	10·4

values are similar for each lithology with the exception of the disturbed sites all on Bishriyya basalt where the effects of grazing and farming practices have clearly had an impact on the distribution of clasts within the surface. There is no significant difference in clast exposure between the undisturbed lithologies, and the large variability within each group is primarily attributed to the decline in exposure at toe slope sites. Clast exposure along the individual transects (Figure 8) appears to indicate distinctive downslope trends on different basalt lithologies, which in turn are related to profile characteristics. The convex Abed slopes maintain a level of clast exposure which reduces dramatically at the toe slope site. By contrast, the concave Scoriacious slopes have declining clast exposure with distance downslope.

As the exhumation or burial of an individual boulder is likely to be influenced by its size, clast exposure data may be subject to bias associated with variation in clast size. The measurement of clast exposure against clast volume (Figure 9A) indicates a wide degree of scatter. The log-linear correlation ($r=0{\cdot}232$, $n=640$) is significant ($\alpha=0{\cdot}05$), but the gradient of the relationship is gentle. When the relationship between clast volume and percentage exposure is examined in each of the sampling sites, 14 sites (21·9 per cent) were found to have a significant positive correlation. Five of the sites are on the slopes disturbed by agricultural activity but otherwise there is no distinct pattern at particular slope positions or lithologies. The correlation coefficients of the exposure–volume relationship at each sampling site are plotted against arithmetic mean diameter of clasts measured from the adjacent quadrat in Figure 9B. The distribution of points is random, suggesting that any effect of clast size in biasing clast exposure data is relatively limited. A further check on possible bias in the exposure data is conducted by comparing the dimensions of the 10 randomly selected clasts with the quadrat sample. The mean arithmetic diameters ($\Sigma A_i + B_i/2n$) of clasts selected for the exposure measurement are, on average, 2·37 cm larger than those from the quadrat sample (equivalent to 12·8 per cent). Some of the deviation is expected in sites where clast exposure is less than 50 per cent as the exposed dimensions of the *A*- and *B*-axes, as measured in the quadrat survey, are less than the actual dimensions. The average difference between samples at sites where clast exposure is greater than 50 per cent is reduced to 1·56 cm. It is suggested that any bias towards the selection of larger clasts for exposure analysis is not major.

Having considered the reliability of exposure estimates and their distribution across slope profiles, correlations between clast exposure and selected slope can be examined. A correlation matrix using all 64 sites yields significant correlations ($\alpha=0{\cdot}05$) between exposure and slope length, height above base, relative relief and slope curvature, but not with either gradient variable (Table II). The strongest univariate correlations with relative relief and with slope length are plotted in Figure 10. It is clear that there are marked variations in the relation for different basalt types with the disturbed sites plotting as

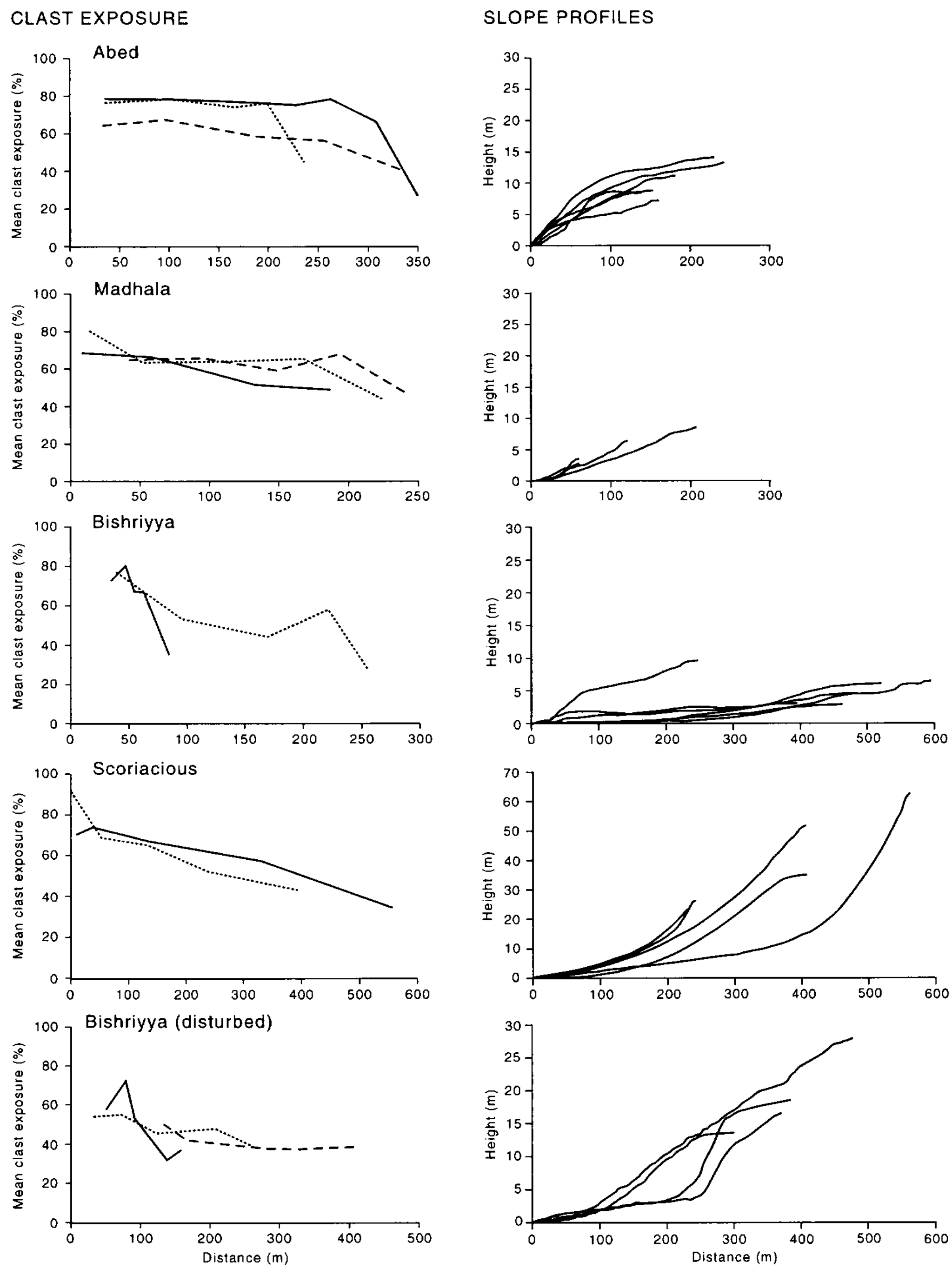

Figure 8. Clast exposure catenas and representative slope profiles on different basalt lithologies

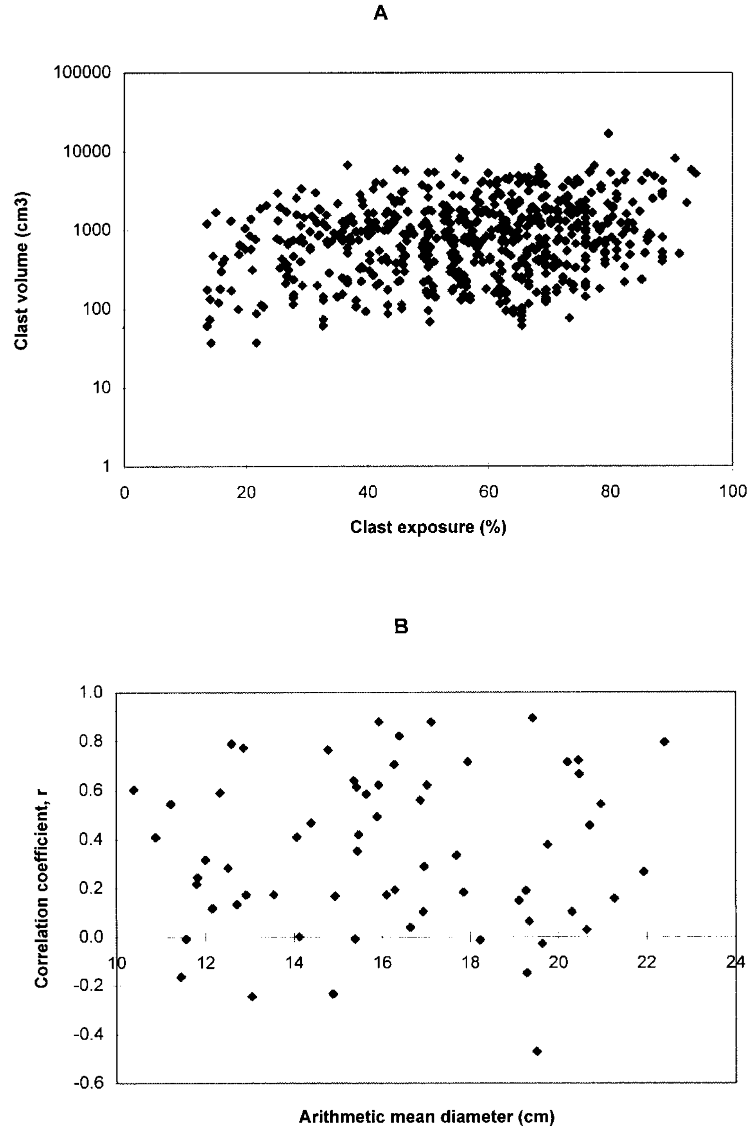

Figure 9. Relationships between clast exposure and size: (A) plot of clast exposure against clast volume for all measured boulders; (B) plot of log-linear correlation coefficients for individual sampling sites against arithmetic mean diameter of clasts from the quadrat sample

outliers to the main relationship. When the disturbed sites are removed from the analysis, the correlations between exposure and slope variables improve. A significant correlation with slope gradient is found and several clast size variables are also correlated with exposure, of which the surface area-weighted mean diameter (Dunkerley, 1995) is the strongest.

The influence of basalt lithology on clast exposure can be examined in two main ways. First, multiple regression techniques incorporating dummy variables representing basalt type can be undertaken to evaluate the amount of variation in clast exposure explained by combinations of slope and lithological variables. Second, the data can be disaggregated according to lithological type and further correlations examined. The lithological categories were added to the multiple regression procedure as dummy variables and the following equation obtained:

Table II. Correlation coefficients for clast exposure against selected ground cover, clast size and slope variables. Significant correlations ($\alpha = 0{\cdot}05$) are indicated by bold typeface

Group	Variable	Correlation coefficient (all data, $n = 64$)	Correlation coefficient (disturbed sites excluded, $n = 49$)
Cover characteristics	Ground cover (%)	**0·483**	**0·421**
	Number of clasts in quadrat (n)	**0·415**	**0·299**
	Total edge length ($m\,m^{-1}$)	**0·460**	**0·362**
Clast size characteristics	Arithmetic mean diameter (cm)	0·136	0·259
	Surface area-weighted mean diameter (cm)	0·235	**0·444**
	Perimeter-weighted mean diameter (cm)	0·188	**0·362**
	Surface area/edge length ratio	0·169	**0·341**
Slope characteristics	Distance downslope (slope length) (m)	**–0·631**	**–0·666**
	Height above base (m)	**0·386**	**0·435**
	Relative relief (%)	**0·665**	**0·760**
	Slope gradient (°)	0·221	**0·298**
	Quadrat gradient (°)	0·107	0·248
	Slope curvature (°/100 m)	**–0·413**	**–0·347**
	Zingg coefficient	0·001	0·124

$$EXP = 0{\cdot}162\,R - 0{\cdot}102\,\theta - 0{\cdot}250\,C_v - 0{\cdot}36\,L + 0{\cdot}484\,D_a - 4{\cdot}1\,Abed - 6{\cdot}7\,Bish - 5{\cdot}3\,Madh - 19{\cdot}9\,Dist \quad R^2 = 0{\cdot}6772,\ n = 64$$

where EXP = clast exposure (per cent), R = relative relief (per cent), θ = slope gradient (degrees), C_v = slope curvature (degrees per 100 m), L = slope length (m) and D_a = surface area-weighted mean clast diameter (cm). *Abed*, *Bish*, *Madh* and *Dist* are dummy variables (Abed, Bishriyya, Madhala and Disturbed sites) taking a value of 1 when that lithology is selected or 0 otherwise.

If the clast size variable D_a is removed from the analysis, the R^2 value declines very slightly, such that about two-thirds (66·3 per cent) of the variation in clast exposure is explained in terms of the four slope variables and lithology. A separate analysis was undertaken dropping the data from disturbed sites. In this case ($n = 49$), 61·2 per cent of the variation in clast exposure is explained by the same four slope variables and D_a but is not improved much by the inclusion of lithological dummy variables.

Separating the data by basalt type, all four lithologies are found to have significant correlations with slope length and relative relief (Table III). Only the Scoriacious sites exhibit a relation between clast exposure and slope gradient, while Scoriacious and Madhala sites exhibit a relation between exposure and surface area-weighted mean diameter. None of the individual lithologies yield significant relationships between clast exposure and slope curvature.

CHARACTERIZING CLAST EXPOSURE CATENAS

The multiple regression indicates that a large proportion of the variability in clast exposure on basalt boulder slopes can be explained by basic slope variables and lithology. As ground surface characteristics must be adequately described to parameterize models of hydrological processes, consistent variations in surface characteristics, such as clast exposure, may be important for the application of such models. In turn, the development of distinctive patterns of clast exposure along slope profiles (Figure 8) testifies to the importance of runoff and sediment transport mechanisms in modifying surface characteristics over

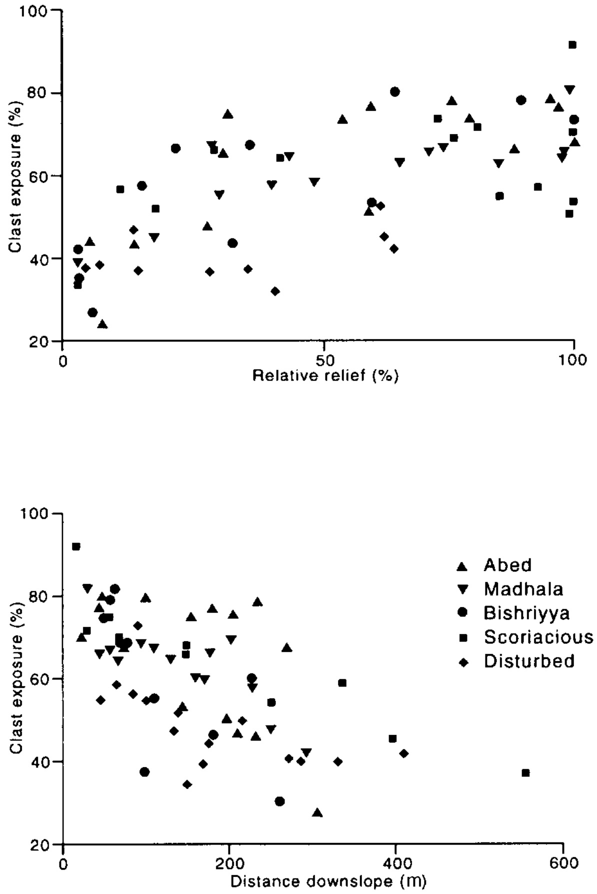

Figure 10. Plots of clast exposure against distance downslope and relative relief for each of the geological categories

Table III. Correlations between clast exposure and selected slope and size variables on individual lithologies (correlation coefficients significant at $\alpha = 0{\cdot}05$; n.s. = not significant)

Basalt type	Sample size	Slope length	Relative relief	Slope gradient	Area-weighted mean diameter
Abed	15	0·572	0·740	n.s.	n.s.
Madhala	14	0·802	0·767	n.s.	0·553
Bishriyya	10	0·724	0·741	n.s.	n.s.
Scoriacious	10	0·925	0·869	0·746	0·765

long periods of time. Having established general relationships between clast exposure and slope variables, it is desirable to develop a model to explain boulder surface catenas. It is possible to characterize the downslope trend in clast exposure by fitting second-order polynomials to the data, which can then be compared with variables describing profile shape. In an earlier discussion of slope characteristics in eastern Jordan (Allison and Higgitt, 1998) a height–length integral, termed the Kennedy parameter, was used to quantify degrees of profile convexity or concavity. Although there appears to be some correspondence between downslope changes in clast exposure and overall profile

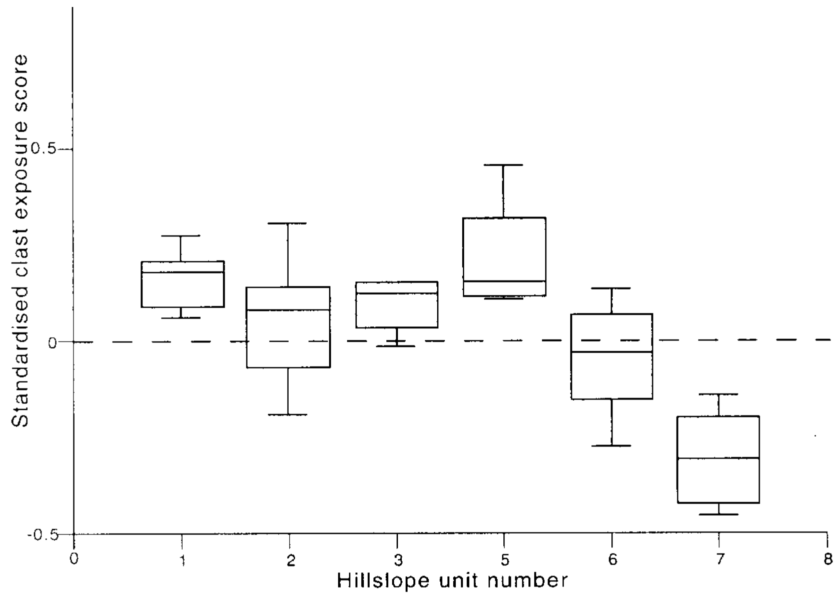

Figure 11. Box plot of clast exposure data for classes on the nine-unit hillslope model. The criteria used in the definition of units are: unit 1, slope crest sites $<2°$; unit 2, convex element 2–4°; unit 3, convex element $>4°$; unit 5, 'transportational midslope' – concave to rectilinear $>8°$; unit 6, 'colluvial footslope' – concave element $<8°$; unit 7, 'alluvial toeslope' – toeslope locations grading into playa or wadi sediments

shape, the limited sample size and the additional variability imparted by lithology obscures any clear statistical relationship. Nor is it possible to relate clast exposure characteristics to any simple index of erosion potential (such as the coefficient of Zingg (1940), $\tan^{1{\cdot}4}\theta\, L^{0{\cdot}6}$) as this does not allow for the influence of deposition on lower slope positions.

An alternative approach is to assign sample sites to semi-quantitative slope classes such as the Dalrymple *et al.* (1968) nine-unit hillslope model. The effect of different lithologies can be limited by standardizing clast exposure within each lithological category. The distribution of standardized scores (mean clast exposure divided by the product of standard deviation and square root of sample size) for each slope unit can then be examined (Figure 11). Channel features (units 8 and 9) are not considered in the present study and there are no free faces (unit 4) within the gently undulating Badia landscape. As expected, clast exposure is reduced on colluvial footslope and toeslope locations (units 6 and 7), but the remaining units have overlapping clast exposure ranges. The highest mean exposure is found in unit 5, defined by Dalrymple *et al.* (1968) as a transport element, which is consistent with a controlling process of slope wash.

In conclusion, observations that the characteristics of boulder-mantled slopes change downslope because of the transport and accumulation of slope wash sediments have been confirmed by quantitative analysis of clast exposure along 13 slope profiles in the Eastern Badia of Jordan. The absolute and relative volumes of clasts exposed above and buried within the substrate can be established because of the staining of clasts in contact with the underlying sediments. An elliptic function for calculating partial volumes performs well in comparison to a method based on ratios exposed and buried perimeters. Provided that the majority of clasts approximate ellipsoids and the staining is contemporaneous to contact with the sediment, measurements of clast exposure can be obtained rapidly. In turn, these may be helpful in characterizing hydrological response on different pavement lithologies or at different parts of hillslopes.

ACKNOWLEDGEMENTS

The study has been conducted as part of the Jordan Badia Research and Development Programme, supported by the Royal Geographical Society (with the Institute of British Geographers), UK, and the Higher Council for Science and Technology, Jordan. We acknowledge the financial support provided by BRDP sponsors and by the University of Durham Research Initiatives Fund. We are grateful to BRDP workers for logistic support in the field and to Dr N. J. Cox for discussions about ellipsoid geometry.

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